A NOTE ON THE STRENGTH OF JAMAICA GROWN BAMBOO

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(Received 17 November 1978)

ABSTRACT

The results of approaches at developing and analysing empirical representations of axial tensile properties of the tissue of *Bambusa vulgaris* Schrad are described. The correlation between the tensile strength of the cell-wall tissue and the measured gross density is lower for small specimens, reinforced by strong narrow lumen fibers, than for larger specimens that contain additional broad lumen parenchyma cells.

Keywords: Tensile strength, Young's modulus, wall substance (tissue) density, measured gross density, density patterns.

INTRODUCTION

It is well established that the mechanical properties of naturally occurring cellulose-based materials correlate very well with density (Davis 1955; Mark 1967). In addition the tensile strength and Young's modulus of cellulose fibers both decrease with increasing microfibril angle (Rebenfeld 1965; Page et al. 1972). Correlations of more than 60% have also been observed between bending strength and Young's modulus for cottonwood and oak wood (Walters and Reiss 1977). The dependence of true tensile strength, σ_f, on measured gross density, ρ_m, and true Young's modulus, E, is presently confirmed for *Bambusa vulgaris* Schrad by experimental results.

It is also shown that a high σ_f-E correlation exists for specimens consisting of bundles of 5–100 narrow lumen fibers and in a few cases xylem vessels. Such segments had a lower σ_f-ρ_m correlation than the much larger samples that had many bundles of narrow lumen fibers and xylem vessels, as well as additional broad lumen parenchyma cells.

METHODS OF ANALYSIS

All tests were performed under ambient conditions (28 C, 70% RH) and all straining speeds were approximately $0.7 \times 10^{-3} s^{-1}$.

Large specimens

The gross densities of samples cut and shaped rectangularly for Young's moduli determination were estimated from dimensions measured with a Vernier caliper, a micrometer, a meter rule, and a 2-kg balance. The specimens had lengths of about 300 mm and cross-sectional areas in the range 30–300 mm^2: a wide range of areas was chosen to ensure that there was no significant size effect among the large specimens. The Young's moduli parallel to the axes of the reinforcing fibers were determined by the three point bend method. Results of thirteen experiments performed on ten samples were obtained: these results include two repetitions on three samples, each in an inverted position to certify that there was no significant

Wood and Fiber, 11(2), 1979, pp. 86–91

FIG. 1. An example of large *Bambusa vulgaris* Schrad samples fractured in tension.

difference between the inner and outer surfaces of the *Bambusa vulgaris* Schrad stem. The same samples were reduced to dumbbell-shaped specimens having their narrow regions in the range 10–100 mm^2: this reduction prevented samples from failing as a result of pressure increases at the grips during extension.

The tensile strengths were measured parallel to the axes of the fibers using a Monsanto tensometer type TEK/2/9125 to produce the type of fracture shown in Fig. 1.

Small specimens

Samples with cross-sectional areas in the range 0.004–0.025 mm^2 were easily extracted from the fractured regions of large samples illustrated in Fig. 1. The mass (m) of each small specimen was measured, using a Mettler microbalance type M-5. The length (l_s) was estimated by placing a transparent scale over the specimen, which was held just taut by fixing the ends to a glass slide with transparent adhesive tape. Gross density was calculated using the cross-sectional area determined from dimensions obtained by examination of the specimen with an Olympus optical microscope type 202714 in the transparent mode. With the image of each specimen projected upon the ground glass screen of the microscope, cross-sectional dimensions were directly measured using a graticule superimposed on that image. It was ensured at this stage that the cross-sectional areas of each specimen to be mounted did not deviate as much as 10% along its length.

Specimens were glued to brass mounts at gauge lengths in the range l_0 = 20–

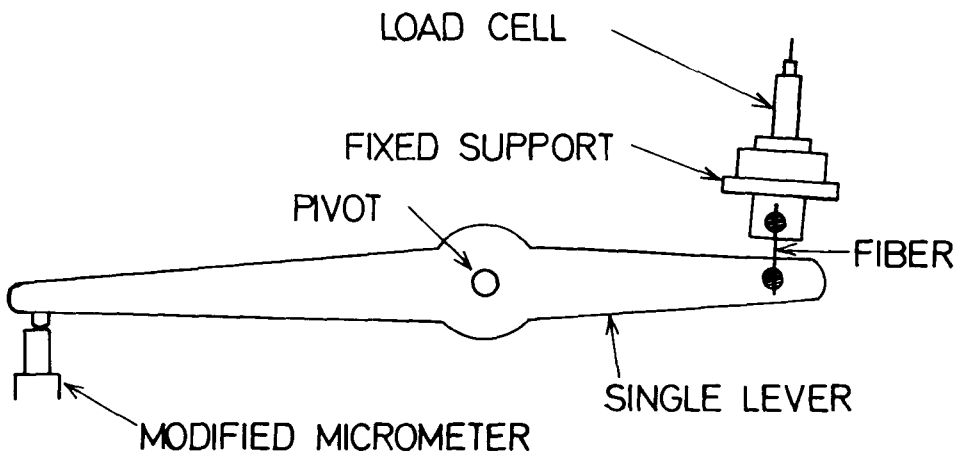

FIG. 2. Fiber microtensometer used to fracture small specimens.

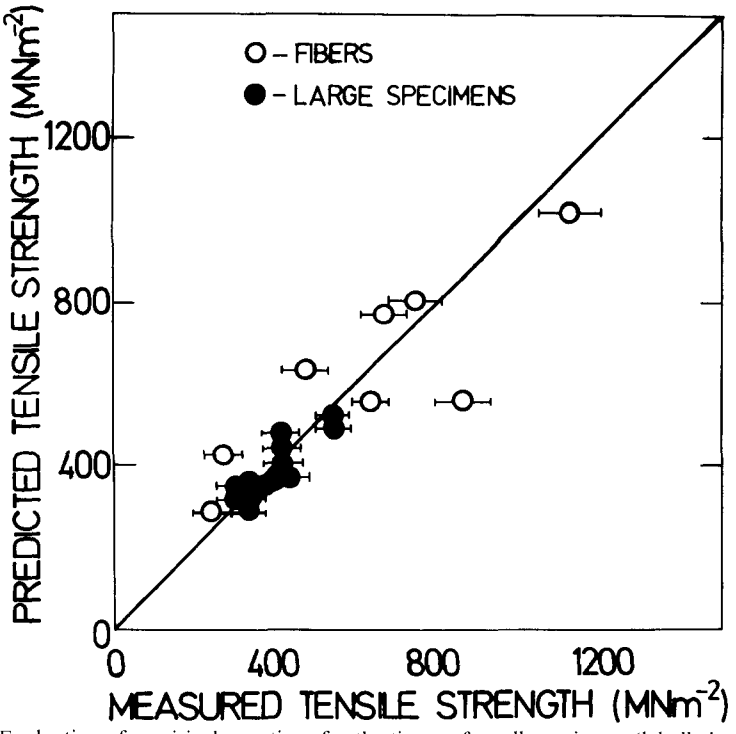

FIG. 3. Evaluation of empirical equations for the tissue of small specimens (labelled as fibers) and large specimens.

23 mm. A bamboo sliver was attached parallel to every specimen to facilitate careful transfer of the specimen and specimen mounts from initial locations on racks, to the circular locating holes of a specially designed microtensometer described in Fig. 2. The sliver was removed and the specimen prevented from bending at its ends by rotating the mounts to obtain direct axial alignment of the fibers within the specimen and the load cell. The gauge length (l_0) was measured using the transparent rule prior to extending the specimens to fracture. Reactions to the calibrated sensitive load cell were amplified and recorded on an x-t plotter. The Young's modulus determination from the x-t slope was dependent on (1) a factor making allowance for the speed of the motor-driven micrometer, the arms ratio of the lever, and the speed of the recording paper; and (2) a correction for the strain of the instrument. Tensile strength was obtained using the breaking force estimated from the calibration curve of the load cell. Ten samples were tested, but only the eight (8) that failed in the middle were further analysed.

Microscopy

Portions of the large specimens fractured by the three point bend method provided very informative cross-sectional views when examined using an 1S1-60 scanning electron microscope (SEM). Long segments of the small specimens were also analysed in detail by the SEM, while other segments were embedded in wax, and microtomed sections were obtained for analysis with the optical microscope.

RESULTS AND DISCUSSION

The true mechanical properties were all estimated to within an absolute error of about 10% using the true cross-sectional area. A value of Young's modulus for each large sample was initially calculated in terms of the measured gross properties. This value was finally multiplied by ρ_c/ρ_m, which was the equivalent of the ratio of measured to true cross-sectional area. The well-known value of $\rho_c = 1.5 \times 10^3$ kg m^{-3} for naturally occurring cellulose based tissues (Kellogg et al. 1975) was chosen as the cell-wall substance density. The true tensile strength of each sample was obtained by dividing the breaking force by the true area A_t obtained from the equation:

$$A_t = \frac{m}{\rho_c l_s}, \qquad \ldots \quad (1)$$

where m/l_s, was the mass per unit length of the sample. This equation was also used to calculate the true cross-sectional area of the small specimens prior to discerning both E and σ_f values.

Analysis of data included regressions and correlations of the following:

(i) σ_f vs ρ_m
(ii) σ_f vs E; and
(iii) σ_f vs ρ_m and E.

A much higher tensile strength-density correlation coefficient of r = 0.80 was obtained for the large specimens than for fibers with r = 0.30. In reverse, the tensile strength-Young's modulus correlation coefficient was only r = 0.48 for the large samples compared to r = 0.77 for the fibers.

It was from the third of these approaches that the best coefficient between predicted and measured results was obtained from the following regression equations:

$$\sigma_f = 0.76\rho_m + 2.25 \times 10^{-9}E - 131(\text{M Nm}^{-2}) \qquad \ldots \quad (2)$$

for the large samples, with r = 0.841 for more than 99.9% significance.

$$\sigma_f = 0.25\rho_m + 21.4 \times 10^{-9}E - 443(\text{M Nm}^{-2}) \qquad \ldots \quad (3)$$

for the fibers with r = 0.847 for more than 99.0% significance. The controlling properties were E = 19 – 55 G N m^{-2} and $\rho_m = 0.45 - 0.65 \times 10^3$ kg m^{-3} for the large samples, while E = 25 – 60 G N m^{-2} and $\rho_m = 0.30 - 1.5 \times 10^3$ kg m^{-3} for the fibers. The former all failed with about 1% strains and the fibers within 1–3%. The results of using Eqs. (2) and (3) are illustrated in Fig. 3. It is shown that although large samples had comparable E values, their mean tensile strength was 50% lower with σ_f = 300–550 M Nm^{-2} compared to 270–1100 M N m^{-2} for fibers.

The properties based on the measured gross cross-sectional area A_m, instead of A_t, obviously included greater tensile strength-Young's modulus correlation coefficients for large specimens with r = 0.79, as well as for small specimens with r = 0.92. This is the result of the similar contribution of lumen space, xylem

FIG. 4. Cross-section of large specimens showing (1) bundles of narrow lumen fibers, (2) very large xylem vessels, and (3) broad lumen parenchyma cells.

vessels, and lysignic intercellular spaces to both tensile properties of an individual specimen. The correlation coefficients of tensile strengths (based on A_m) against density were similarly increased to values of $r = 0.91$ for the large specimens and $r = 0.76$ for the small specimens. However, the greater dependence of the tensile strength of the smaller specimens on Young's modulus is also confirmed by these results.

In addition, SEM analysis showed that small specimens extracted from the fracture zones of the larger samples described in Fig. 1 contained no induced defects such as microcracks.

The reduction in dependence on gross density when a large specimen (illustrated in Fig. 4) is replaced by a small specimen, which is effectively a bundle of fibers, means that the larger parenchyma cells are generally weaker in tension. An increase in the number density of fibers possessing high mean density $\bar{\rho}_m = 0.91 \times 10^3$ kg m^{-3} would increase the density of the large sample within the measured range $\rho_m = 0.45 - 0.70 \times 10^3$kg m^{-3}. The high $\sigma_f - \rho_m$ correlation obtained was associated with this increase. Furthermore σ_f refers to strengths estimated for the cell-wall substances and not for the lumens and void spaces as a whole. Therefore the large cells must necessarily possess weaker walls compared to the cell walls of the fibers that replace them to produce higher strength tissue in the denser large specimens. Second, the greater dependence of tensile strength on Young's modulus for small specimens means that they should have greater microfibril contribution. This would enable the tissue of their reinforcing fibers to achieve greater strengths especially for low microfibril angles. Evidence of greater strengths is illustrated in Fig. 3 for some small specimens.

CONCLUSION

Best empirical representations of the true tensile strengths of the tissue of *Bambusa vulgaris* Schrad are dependent on the gross density as well as the

Young's modulus for small and large specimens alike. However, a size effect arises since the correlation between the tensile strength of the tissue and gross density is lower for small specimens than for large specimens. The higher mean density of the reinforcing fiber bundles, combined with the associated greater dependence on Young's modulus for the tissue of these bundles, provides further support for the present observations. The observations show that some of the fiber bundles have stronger tissues than the parenchyma cells.

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